

Estimation of the neutrino flux and resulting constraints on hadronic emission models for Cyg X-3 using *AGILE* data

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ABSTRACT

In this work we give an estimate of the neutrino flux that can be expected from the microquasar Cyg X-3. We calculate the muon neutrino flux expected here on Earth as well as the corresponding number of neutrino events in the IceCube telescope based on the so-called “hypersoft” X-ray state of Cyg X-3. If the average emission from Cyg X-3 over a period of 5 years were as high as during the used X-ray state, a total of 0.1 events should be observed by the full IceCube telescope. Using the correlation of *AGILE* data on the flaring episodes in 2009 Jun.–Jul. to soft X-ray states we calculate that the upper limits on the neutrino flux given by IceCube are starting to constrain the hadronic models, which have been introduced to interpret the high energy emission detected by *AGILE*.

Key words. Neutrinos, Methods: numerical, Cygnus X-3, Microquasars

1. Introduction

Microquasars (MQ) are Galactic X-ray binary (XRB) systems, which exhibit relativistic radio jets (Mirabel & Rodriguez (1999); Fender (2001)). These systems are believed to consist of a compact object, a neutron star or a black hole, and a giant star companion. Mass transfer from the giant star to the compact object through the formation of an accretion disc and the presence of the jets make them similar to small quasars, hence their name “microquasars.” The analogy may not be only morphological; although there is no obvious scaling, it is common thinking that the physical processes that govern the formation of the accretion disc and the ejection of plasma into the jets are the same for both systems. Local, Galactic microquasars may therefore be considered as nearby “laboratories,” where models of the distant, powerful quasars can be tested. The observed radiation from microquasar jets, typically is in the radio and in some cases also in the IR band and it is consistent with non-thermal synchrotron radiation emitted by a population of relativistic, shock-accelerated electrons.

The composition of microquasar jets is still an open issue. The synchrotron emission both in the radio and in the IR is consistent with near equipartition between electrons and magnetic field, which is also implied by minimum energy considerations (Levinson & Blandford (1996)). However, the dominant energy carrier in the jet is presently unknown. A possible diagnostic of hadronic jets, namely the emission of TeV neutrinos, has been proposed by Levinson & Waxman (2001). They have shown that, for typical microquasar jet parameters, protons may be accelerated in the jet to $\sim 10^{16}$ eV, and that the interaction of these protons with synchrotron photons emitted by the shock accelerated electrons is expected to lead to 1–100 TeV neutrino emission. The predicted fluxes are detectable by large, km²-scale

effective area, high-energy neutrino telescopes, such as the operating south pole detector IceCube, see Ahrens et al. (2003). Distefano et al. (2002) have extended the work of Levinson & Waxman (2001) and predicted the neutrino flux for several microquasars whose radio data were available in the literature. They found that the largest number of neutrinos from bursting MQs is expected to come from Cyg-X3 and XTE J1118 +480.

The *AGILE* team has made a detailed study of γ -ray emission from Cygnus X-3 with the *AGILE* satellite. The *AGILE* discovery of transient γ -ray emission from Cygnus X-3 in 2008 Apr. associated with a specific spectral state preceding a major radio jet ejection opened a new window of investigation of microquasars. Several other major γ -ray emission episodes from Cygnus X-3 have been detected by *AGILE* and *Fermi* since 2008 (Tavani et al. (2009); Fermi LAT Collaboration et al. (2009)). The *AGILE* discovered several transient γ -ray emission episodes from Cygnus X-3 in the energy range 100 MeV – 50 GeV during the periods 2009 Jun–Jul and 2009 Dec.–2010 mid-Jun. They found that the γ -ray emission from Cygnus X-3 is detectable by *AGILE* not only during relatively short (1-2 day) flares as in Tavani et al. (2009) but also during extended periods lasting several days or weeks (as during 2009 Jun-Jul) (Bulgarelli, A. et al. (2012)). Detecting continuous γ -ray emission during “active” phases is of great theoretical relevance for the modeling of Cygnus X-3.

The main mechanism at the origin of the high energy emission detected by *AGILE* can be the Inverse Compton scattering of high energy electrons accelerated in the source with low energy photons emitted by synchrotron process (Dubus et al. (2010)). However another possibility, if hadrons are present in the jet, is that the 100 MeV – 50 GeV emission is due to π^0 decay into TeV γ -rays that trigger a cascade to GeV gamma-rays. These π^0 may be produced in

the jet by photohadronic interactions or by proton-proton collisions between protons in the jet and protons in the gaseous surroundings provided by the WR companion mass outflow (Piano et al. (2012); Romero et al. (2003)).

In this paper we use a simplified jet model to estimate the number of neutrinos expected from Cyg X-3 based on the X-ray data taken in 2009 during an episode of flares. In Section 2 we describe the simplified model we use for the jet of the microquasar and the photohadronic interactions happening inside of it. In Section 3 we derive the expected photon and proton densities inside the jet of Cyg X-3, which are needed for the simulation of the photohadronic interactions, from the observed X-ray data. In Section 4 we then use the derived densities to estimate the expected neutrino number both in the case that the emission is due to IC and in the case that is due to π^0 decay into γ -ray photons. In Section 5 we discuss our results.

2. A simplified jet model

In this section we want to describe our simplified jet model. The model we want to apply to the microquasar Cyg X-3 was originally used for GRB which are also assumed to originate from emitting jets. The main simplification is that we totally neglect the dynamic of the propagating jet and assume that the outflow is static. The high energy protons as well as the X-ray and γ -ray photons are assumed to be present in one interaction zone and emission will only originate from this one emission region. Both the proton as well as the photon density are assumed to be isotropic in the plasma rest frame of the jet. These assumptions are essential for us to use the photohadronic interaction code based on Hümmer et al. (2010b) (model Sim-B), which is an analytical parameterization based on SOPHIA, see Mücke et al. (2000). Starting from the particle densities the code calculates the result of the photohadronic interactions leading to secondary particles which subsequently decay into neutrinos. It is based on an analytical parameterization of the full photohadronic interaction cross section and includes features such as individual treatment of secondary particles, helicity dependent muon decay, as well as neutrino flavor mixing, for details see Hümmer et al. (2010a). With this treatment we also incorporate the magnetic field effects discussed by Reynoso & Romero (2009), which do play a role due to the assumption of neutrino production in the internal shocks.

We assume in concordance with Levinson & Waxman (2001) that the photon energy density inside the jet U'_γ can be calculated from the emitted luminosity L of the source by considering the emission passing the surface of the jet

$$U'_\gamma = \frac{L}{4\pi (l^2 \cdot \sin^2(\theta_j)) c \mathcal{D}^2} \quad (1)$$

with l being the distance of the emission region from the central object, \mathcal{D} the Doppler factor of the jet, and θ_j the opening angle of the jet. Note that the boost with the Doppler factor is needed since U'_γ is the energy density inside the shock frame. Additionally, we know that the photon energy density can be defined as

$$U'_\gamma = \int E'_\gamma n'_\gamma dE'_\gamma \quad , \quad (2)$$

with n'_γ the photon spectrum in particles per volume and per energy. For our photohadronic interaction calculation

we will need n'_γ . The shape of this spectrum can be obtained from the photon data while the normalization can be obtained using Eq. (2).

Hence, by knowing the observed (energy integrated) photon flux F_γ we can calculate the (isotropic equivalent) luminosity $L = 4\pi D_L^2 F_\gamma$, and subsequently the photon particle density inside the jet. Moreover it is possible to calculate the energy carried by the magnetic field B as well as the energy in protons from energy equipartition arguments. Following the considerations of Levinson & Waxman (2001) it is possible to estimate the magnetic field B' (in G) by

$$B' = \sqrt{8\pi \frac{\varepsilon_B}{\varepsilon_e} U'_\gamma} \quad (3)$$

with ε_B being the fraction of the jets total energy carried by magnetic field, ε_e the fraction carried by electrons/photons, and U'_γ from Eq. (1) in erg s^{-1} . Accordingly we can estimate that the energy density carried by protons is

$$U'_p = \frac{\varepsilon_p}{\varepsilon_e} \cdot U'_\gamma \quad (4)$$

with ε_p being the fraction of the jets total energy carried by protons. The fractions are estimated to be of the order of 0.1, see Distefano et al. (2002); Levinson & Waxman (2001). Moreover, we can connect the proton spectrum n'_p to the energy density in protons U'_p by adapting Eq. (2) for protons. However, opposite to the photon spectrum, we do not have any direct observational information on the shape of the proton spectrum. From considerations on the Fermi acceleration we know that the spectrum should have a form $\propto E^{-\alpha_p}$ with $\alpha_p \simeq 2$. Furthermore, we know that particles can only be accelerated to finite energies and a cut-off at a critical energy E_c should be expected.¹ We can estimate the critical proton energy by basic considerations on the jet properties. In general two limiting scenarios are considered: the synchrotron limited case and the escape limited case. In the first case the size of the acceleration region is sufficiently large to not affect the particle acceleration and only synchrotron losses limit the maximal particle energy. By comparing the acceleration time to the synchrotron loss time it is possible to obtain the critical energy (in plasma rest frame)

$$E'_{c1} = 2.01 \cdot 10^{11} \sqrt{\eta} \left(\frac{B'}{1 \text{ G}} \right)^{-\frac{1}{2}} \text{ GeV} \quad (5)$$

with η the acceleration efficiency and B' the magnetic field in the plasma rest frame. For all the calculations in this paper we have assumed $\eta = 0.1$. In the second case the energy of the protons is limited by the maximal energy the particles can reach before they escape the source. Effectively this is equivalent to comparing the size of the region to the Larmor radius of the particles. Hence, this critical energy can be estimated by comparing the acceleration time to the escape time from the jet which leads to

$$E'_{c2} = 3 \cdot 10^9 \eta \left(\frac{l}{10^{14} \text{ cm}} \right) \cdot \sin(\theta_j) \left(\frac{B'}{1 \text{ G}} \right) \text{ GeV} \quad . \quad (6)$$

The smaller of the two critical energies is the relevant critical energy for a given set of parameters.

¹ The cut-off we assume for our calculations is of the form $\exp(-(E/E_c)^2)$, however the actual shape of the cut-off is not relevant. Only the position, given by critical energy E_c , is.

3. Observational data on Cyg X-3

The information on Cyg X-3 is comparably well documented and there already have been earlier studies on the neutrino emission of this source, such as Distefano et al. (2002). For our study we adopt the following parameters for the source:

$$\begin{aligned} D_L &= 7.2 \text{ kpc} \quad , \\ \mathcal{D} &= 2.74 \quad , \\ \theta_j &= 12^\circ \quad , \\ l &= 10^8 \text{ cm} \quad . \end{aligned}$$

D_L is the distance between Earth and the source, with the result taken from Ling et al. (2009). The value of the Doppler factor \mathcal{D} is the result of an assumed Lorentz factor $\Gamma = 1.70$ and a viewing angle $\theta = 14^\circ$, taken from Distefano et al. (2002); Mioduszewski et al. (2001). The jet opening angle θ_j is also taken from Mioduszewski et al. (2001). The value for the radius of the emission region l is set to the assumed collision radius of internal shocks in a microquasar, as in Levinson & Waxman (2001).

In a second step we need to take into account the kinematics of the photohadronic interactions to estimate which energy range of photons can act as the target photons for our highest energy protons. Assuming a maximal proton energy of 10^8 GeV we can estimate that X-ray photons with several keV energy are needed for producing the Δ -resonance. For this reason we will use X-ray data from Koljonen et al. (2010) as our target photons. Since we are interested in the phase directly before a flare we will use data for the hypersoft state from said paper. The used data ranges from 3.5 up to 102 keV, with the integrated luminosity we obtain being $L_\gamma = 3.77 \cdot 10^{37} \text{ erg s}^{-1}$. With help of Eqs. (1) and (2) we can normalize our target photon density. Furthermore we can estimate that for the given L_γ the resulting magnetic field from Eq. (3) is $B' = 8.8 \cdot 10^5 \text{ G}$, while the resulting maximal proton energy is $E'_{p,c} = 5.5 \cdot 10^7 \text{ GeV}$, given by Eq. (6). Hence we can normalize the proton density as well through Eq. (4). The density, which we obtain using this method, corresponds to an injection rate of $3.3 \cdot 10^{22} \text{ protons cm}^{-2} \text{ s}^{-1}$.

4. Expected neutrino flux

With the normalized spectra we obtained in the previous section we can calculate the shape of the neutrino flux at Earth after flavor mixing. Especially the shape of the muon neutrino flux is relevant for the current neutrino experiments such as IceCube. Our photohadronic interaction cross section includes several contributions apart from the Δ -resonance such as higher resonances, direct production of pions (t -channel), and high energy processes leading to multiple pions. For the flavor mixing we still assume a scenario with $\theta_{13} = 0$ even though Daya Bay, see An et al. (2012), and RENO, see Ahn et al. (2012), have ruled this out. However, it was already shown that the effect of different values of the neutrino mixing angles inside the current uncertainty on the neutrino flux prediction is comparably small, see Baerwald et al. (2011), and can be neglected at this stage. In Fig. 1 we plot the expected muon neutrino (and antineutrino) flux (in $\text{GeV cm}^{-2} \text{ s}^{-1}$) for Cyg X-3 in this simple model of a microquasar jet as a blue solid curve. The shape of the spectrum is similar to the ones predicted

for GRB since we apply the same assumption of a neutrino flux originating from internal shocks. Hence we can see the same splitting into a double peak from muon and pion decay plus an additional component from kaon decay, as in Baerwald et al. (2011). It is still significantly below the detection limit of IC59 during the time the flares were recorded (assumed exposure of 61 days, black solid curve), and if one extrapolates to the full IceCube detector and 5 years of exposure the neutrino flux would just start to be in the detectable range (black dashed curve). Note that the here depicted limits are based on the solid-angle-averaged effective areas at final cut level of the time-integrated point-like source search from Abbasi et al. (2011). We use the band for $\delta = (30^\circ, 60^\circ)$ from the left plot of Fig. 8 of said reference, which should be suitable for Cyg X-3 ($\delta = 40^\circ 57'$). Even though this effective area is already at the final cut level it still needs to be considered that the neutrino signal needs to be distinguished from the background of atmospheric neutrinos. There are however possibilities to improve the cuts, such as additional cuts in the timing as done in Abbasi et al. (2012) for Cyg X-3 flares. Additionally we have scaled the effective area up from the given values for the 40-string configuration to the 59-string (multiplied by 1.3) and 86-string configuration (multiplied by 2.4). Therefore the actual effective areas for IC59 and IC86 point source searches may actually be slightly different, but were not publicly available during our work.

Moreover, it can be seen that the predicted neutrino flux above 10^5 GeV is already one order lower than the peak value and the flux drops off even more above PeV energies. Therefore, it should be unlikely that Cyg X-3 is a possible source for the two unidentified PeV cascade events in IceCube, see talk by Ishihara (2012) at Neutrino2012, as events at lower energies, *i.e.* between 10^4 and 10^5 GeV , are far more likely. Furthermore, the number of events can be calculated from the flux prediction and the detector parameters using the formula

$$N = \int dE A_\nu^{\text{eff}}(E) t_{\text{exp}} \frac{dN(E)}{dE} \quad (7)$$

with $A_\nu^{\text{eff}}(E)$ being the energy dependent effective area (of IceCube), t_{exp} the exposure, and $dN(E)/dE$ the (muon) neutrino spectrum (on Earth, after flavor mixing). We obtain that we would expect 0.002 events in IceCube for the time of the flares in June and July of 2009 (59 strings) and a total of 0.12 events over 5 years in the full detector. Especially this first result of no events in IC 59 is (in a sense) reassuring as it is consistent with the current IceCube data, which so far does not suggest any UHE neutrinos apart from the atmospheric ones, see Abbasi et al. (2012). Moreover, it should be possible to constrain elements of this simple microquasar model with in 5 to 10 years of data taking with the full detector if the flares continue. We are aware that this model is very simple and does not even try to explain the dynamic of a microquasar jet. However, as neutrino measurements are at this stage not even close when it comes to the time resolution compared to photon measurements, it is reasonable to average out most of the variations.

Neutrinos from π^0 decay

We now want to test how many neutrinos would be expected if the observed γ -ray emission by *AGILE* was actu-

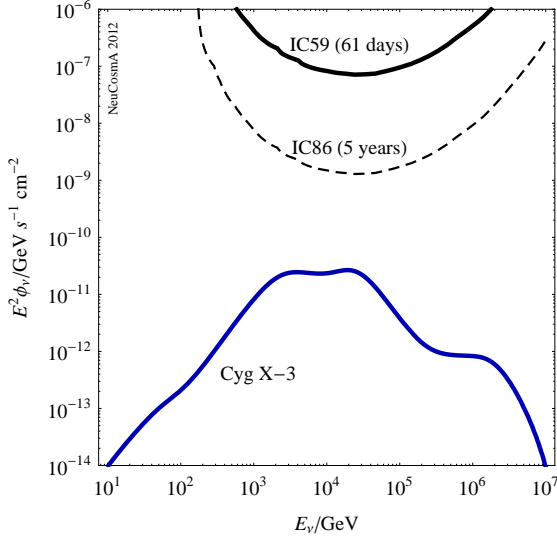


Fig. 1. In this plot we show the expected neutrino flux from Cyg X-3 derived for a simplified model of the microquasar jet, based on hypersoft X-ray data from Koljonen et al. (2010) (blue solid curve). For comparison we give the (extrapolated) differential flux limits for IC59 during the 61 days of the flaring episodes (solid black curve) as well as an extrapolation of the expected one for IC86 (full detector) after 5 years of data taking. As one can see both do not reach the flux of this single microquasar, even though the full detector could with a longer exposure. The differential limits are based on the solid-angle-averaged effective areas at final cut level of the time-integrated point-like source search from Abbasi et al. (2011).

ally coming from the decay of photohadronically produced π^0 into photons. The photons from such decays would have to cascade down to lower energies and may lose a part of their energy during this process. However, here we only want to estimate the number of expected neutrinos for the case that the observed GeV-emission is due to π^0 decays. Hence, it is sufficient to assume energy conservation for the calculation. With this approach it is possible to set a lower bound on the expected amount of neutrinos. In case of energy losses during/after the cascading process an even higher amount of original π^0 (and consequently π^+) would be needed, and hence an even higher neutrino flux would be expected. If one assumes that

$$\int_{10 \text{ MeV}}^{10 \text{ GeV}} dE_\gamma E_\gamma \frac{dN_\gamma(E_\gamma)}{dE_\gamma} = \int_{0 \text{ GeV}}^{10^{10} \text{ GeV}} dE_\gamma E_\gamma \frac{dN_\gamma^{\text{HE}}(E_\gamma)}{dE_\gamma} \quad (8)$$

with $\frac{dN_\gamma(E_\gamma)}{dE_\gamma}$ being the observed photon spectrum from Bulgarelli, A. et al. (2012) while $\frac{dN_\gamma^{\text{HE}}(E_\gamma)}{dE_\gamma}$ is the resulting spectrum of high energy photons before cascading to lower energies. The high energy spectrum has been calculated numerically with the photohadronic interaction code, which also has been used for calculating the neutrino spectra. With this method we obtain that the amount of produced π^0 needed to match the observed γ -ray emission is about 2400 times larger than our prediction for π^0 from the calculation in the previous section. As a consequence the nominal amount of expected neutrino events would reach

about 5.2 events for the 61 days of flaring in 2009. This would still need to be distinguished from the $\mathcal{O}(100)$ background events². If the used cuts achieve such a high precision, then it should be possible to rule out if the observed flares are due to the decay of π^0 .

On a similar note it can be stated that models based on pp -interactions might already be more strongly constrained than the photohadronic interaction models. Even though we cannot give a detailed estimate on the level of the proton-photon collisions for the proton-proton interactions we can still give a zeroth order estimate. It is commonly assumed that pp -interactions give a neutrino result which is 4/3 higher than for $p\gamma$. Hence this very rough estimate gives that 0.16 neutrino events should be expected over 5 years or 6.9 events during the flaring episodes for γ -ray flares from π^0 -decay. A more detailed calculation of the neutrino flux prediction from proton-proton interactions, with all features included for the photohadronic interactions, is currently beyond the scope of this paper even though work in this direction was already done, see *e.g.* Reynoso & Romero (2009). A prediction based on a detailed particle physics treatment of pp -interactions should be a goal for the future.

5. Discussion

In this paper we have investigated the possibility that microquasars may be the sources of high energy neutrinos. In particular we have estimated the neutrino flux expected from Cygnus X-3. Starting from the X-ray data for the hypersoft state from Koljonen et al. (2010) we have calculated back to the particle densities of protons and photons inside the jet of Cyg X-3 in the assumption of a simple geometrical model for the jet. The reason for choosing this data set was to use a data for a phase before a radio flare, as suggested by Bulgarelli, A. et al. (2012). This state also fulfills the observed correlation of *AGILE* γ -ray flares in June–July 2009, and November 2009–July 2010 with soft X-ray states and episodes of decreasing or non-detectable hard X-ray emission reported by Bulgarelli, A. et al. (2012). However, in principle any other state could also be used for the calculations, as long as we are able to derive the particle densities inside the jet. We then used the densities to compute the expected neutrino emission from the jet using a numerical code which incorporates the full photohadronic interaction cross section, individual treatment of secondary particles (including losses), and flavor mixing of the neutrinos. The expected muon neutrino flux was then compared to the sensitivity of IceCube (59 strings) during the 61 days of flaring. The expected number of 0.002 events is in concordance with the non-detection of any neutrinos from Cyg X-3 during that period. Assuming an extended period of flaring and a full IC86 detector we expect about 0.1 associated neutrino events in 5 years of data taking. Moreover, the shape of the neutrino flux disfavors a detection at PeV before seeing events at about 10 TeV. Nevertheless, these predictions are still subject to quite large uncertainties due to the error on the jet parameters as well as the used extrapolated effective area of IceCube. Therefore even slightly lower amounts of observed neutrinos may not directly contradict the ba-

² The amount of events is approximated from scaling the amount of events at final selection level from Fig. 4 of Abbasi et al. (2011) down to 61 days (from 375.5).

sic model of microquasars accelerating protons. Still, in the best case it should be possible to see some events from Cyg X-3 with several years of data taking with the full IceCube detector. Moreover, we also tested the hypothesis that the observed γ -ray emission is due to the decay of π^0 from photohadronic interactions into photons. For this we compared the integrated energies in the observed photons detected by *AGILE* to the energy in photons from π^0 decay. In the Δ -resonance approximation the production of π^0 is directly connected to the production of π^+ , and this concept in principle does not change even for a more detailed particle physics treatment of the interactions. Using these calculations we obtained that the amount of energy in π^0 needed to explain the *AGILE* observations would have to have been so high that the number of expected neutrino events would reach about 5 events during the 61 days of flaring. There have, however, been no reported neutrino events in IceCube which could be associated with Cyg X-3 so far, see Abbasi et al. (2012). We can therefore start to rule out that the observed γ -ray emission is due to the decay of π^0 from photohadronic interactions by combining the photon and neutrino data in the coming months. Especially the point source analysis of IC59 would be of great interest in this regard. Moreover, based on the photohadronic estimates and the estimate that the result for proton-proton collisions is larger by a factor of 4/3, it can be assumed that pp -interactions are even stronger constrained than $p\gamma$ -interactions. However, a real simulation of the neutrino flux prediction from pp , based on a detailed particle physics treatment, is still needed for a conclusive picture.

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